Khan, S.A., Pilakoutas, K., Hajirasouliha, I., Garcia, R. and Guadagnini, M. (2018) “Seismic risk assessment for developing countries: Pakistan as a case study”, Earthquake Engineering and Engineering Vibration, 17(4), pp.787-804. https://doi.org/10.1007/s11803-018-0476-3

Seismic risk assessment for developing countries: Pakistan as a case study

Abstract. Modern Earthquake Risk Assessment (ERA) methods usually require seismo-tectonic information for Probabilistic Seismic Hazard Assessment (PSHA) that may not be readily available in developing countries. To bypass this drawback, this paper presents a practical event-based PSHA method that uses instrumental seismicity, available historical seismicity, as well as limited information on geology and tectonic setting. Historical seismicity is integrated with instrumental seismicity to determine the long-term hazard. The tectonic setting is included by assigning seismic source zones associated with known major faults. Monte Carlo simulations are used to generate earthquake catalogues with randomized key hazard parameters. A case study region in Pakistan is selected to demonstrate the effectiveness of the method. The results indicate that the proposed method produces seismic hazard maps consistent with previous studies, thus being suitable for generating such maps in regions where limited data are available. The PSHA procedure is developed as integral part of an ERA framework named EQRAM. The framework is also used to determine seismic risk in terms of annual losses for the study region.

Keywords: *risk management; seismic hazard assessment; developing countries; Pakistan*

1 INTRODUCTION

Extensive human and economic losses in recent major earthquakes (Indonesia 2009, Haiti 2010, Nepal 2015, and Ecuador 2016) highlight the need for appropriate cost-effective Earthquake Risk Assessment (ERA) tools in seismic-prone developing countries. The first step in the ERA process is the Seismic Hazard Assessment (SHA), which may be deterministic (DSHA) or probabilistic (PSHA) (McGuire, 2001). DSHA determines the maximum magnitude event for a seismic source based on historical seismicity and good geological knowledge of the seismic source (Oliveira and Campos Costa, 2006). However, such information is not always available in developing countries, whereas the maximum magnitude event (on its own) for a specific zone is not enough to perform ERA (Thenhaus and Campbell, 2003). On the other hand, PSHA procedures determine a probabilistic solution based on a series of seismic events generated using appropriate probability functions (McGuire, 1976; Hanks and Cornell, 1994; Abrahamson, 2000).

In general, the selection of the approach required to determine seismic hazard at a particular location depends on how the results will be used (Bommer, 2002; Krinitzsky, 2003). For instance, PSHA is usually performed for seismic hazard mapping, development of design codes, and insurance/reinsurance and financial planning for earthquake losses at the country level (Sokolov *et al.,* 2007). Therefore, PSHA is suitable for ERA, where a final goal is to determine earthquake losses at the regional or country level.

Modern PSHA methodology is based on initial work by Cornell (1968), where probability distributions for magnitude and source site distance were used for the first time. Subsequent work by Cornell and VanMarcke (1969) and Cornell (1971) improved the initial approach by including an upper bound on the earthquake magnitude in each region to avoid the inclusion of unrealistically large earthquakes. Algermissen and Perkins (1972) also utilized this method to produce a seismic-hazard map by assuming a point source for each earthquake rupture. However, earthquakes result from the rupture of finite fault segments and, therefore, their sources can be considered to have a finite length on the earth’s surface and not just a point. Der Kiureghian and Ang (1977) studied this effect and recommended that ground motion should be estimated on the basis of the distance from the site to the closest point of the fault rupture projection. This effect is more important for large magnitude earthquakes that often dominate the seismic hazard in plate boundary areas.

Monte Carlo simulation methods can be used for PSHA by considering epistemic uncertainty in the hazard parameters (Shapira, 1983; Musson, 2000) to generate synthetic earthquake catalogues. Each synthetic catalogue represents the earthquakes that could occur in the study region for a given period consistent with past observations. The seismic events in the synthetic catalogues can be positioned anywhere within the seismic zones. The Monte Carlo simulation is an event-based method that does not directly solve the classic probability equations. However, previous research (Musson, 1999; Crowley and Bommer, 2006) showed that by using a large number of simulations, such stochastic PSHA methods can lead to hazard estimates close to the conventional PSHA methods based on the original Cornell's approach. Also, unlike previous studies that also use Monte Carlo method (e.g. Assatourians and Atkinson, 2013)), the approach used in this ERA framework is different because the events in an earthquake catalogue are smudged to generate large number of catalogues by randomising key hazard parameters.

To aid in modelling seismicity within a region based on the modern PSHA methodology, several computer codes were developed in the past such as EQRISK (McGuire 1976), SEISRISK III (Bender and Perkins, 1987), EZ-FRISK (McGuire, 1993), OHAZ (Zabukovec *et al.,* 2000), CRISIS (Ordaz *et al.,* 2003), OpenSHA (Field *et al.,* 2003), EQRM (Robinson and Fulford, 2005), USGS-NSHM (NHSM, 2008), FRISK88MTM (RE, 2009) and GEM (GEM, 2011). These computer software model the seismicity within a seismic zone by assuming a uniform or smoothed variable (using spatial or kernel methods) earthquake occurrence rate. Whilst the above codes have been widely used for PSHA, their methodology is, in general, associated with the following drawbacks:

- The selection of shape, size and orientation of seismic source zones is subjective as it depends on the users' choice/decisions. Studies by Krinitzsky (1993) on the expert opinion PSHA showed that the experts usually chose different orientations, shapes and sizes for the same seismic source zones. Therefore, available seismicity and tectonic information can lead to different seismic hazard assessments depending on the user-selected seismic source zones (Khan, 2011). However, different plausible source models may be consistently accounted for probabilistically by logic trees (e.g. Bommer and Scherbaum, 2008).
- Conventional PSHA methods assume that the historical seismicity distributes uniformly over source zones, or that it is smoothed spatially (Beauval *et al.,* 2006). Therefore, the seismicity is sometimes smoothed over large regions, which spread the possible occurrence of earthquakes in regions without historical seismicity. This may lead to lower estimations of seismicity in locations near the area source, and to higher estimations of seismicity in regions with few or no historical earthquakes (Abrahamson, 2006).
- The maximum magnitudes M_{max} for the seismic sources are determined from the fault lengths or from the seismicity of the area sources. As these M_{max} values are then smeared over the larger area of the seismic source zone, high 'artificial' Peak Ground Acceleration (PGA) values can be attributed to neighbouring regions.
- In current practice, it is assumed that earthquakes with a magnitude below a selected lower bound are not considered in the PSHA as they are not potentially destructive for well-designed structures. Typically, the lower bound is set at a magnitude of 4 to 5 since well-engineered structures are rarely damaged in earthquakes less than this magnitude (Abrahamson, 2006). Also, catalogues are often incomplete for smaller earthquakes (Reiter, 1990). However, the use of a fixed lower bound is a source of inaccuracy as a small magnitude earthquake occurring very close to a site may still produce a high level of ground motion.

Previous studies have proposed approaches where only historical epicentres are need to carry out hazard assessment (Woo, 1996). Such approaches are extremely practical for parts of the world where the observed seismicity cannot be directly associated with geological structures (e.g. active faults), or in areas where scarce earthquake data makes estimation of earthquake recurrence rather problematic.

This article follows this rationale and proposes a practical event-based PSHA methodology to integrate available historical seismicity information with instrumental seismicity. The methodology also takes into account the effects of tectonic setting by considering that, in a given zone, earthquake rupture lines are oriented along known faults. The methodology attempts to address some of the above mentioned drawbacks associated with existing PSHA methods, and aims to be applied mainly in developing countries for which detailed seismic-tectonic information is not readily available. The efficiency of the method is assessed by considering Pakistan as a case study. This article contributes towards developing faster and reliable seismic risk assessments in residential areas of developing countries so as to assist relevant stakeholders and decision-makers on preparedness, emergency response and mitigation actions.

2 PROPOSED PSHA APPROACH

The flowchart in Figure 1 shows the various components of the proposed PSHA methodology, whereas the subsequent sections describe in detail the steps involved in the calculations.

2.1 Generation of Synthetic Earthquake Catalogs

As shown in Figure 1, the proposed PSHA methodology starts with the creation of a catalogue of seismic events, based on the historical and instrumental seismicity of the region. Seismic zones are then assigned preliminarily to determine the fault type and direction of fault associated with the event under consideration. Monte Carlo simulations are then used to randomize key hazard parameters so as to reflect their uncertainty and generate a large number of synthetic earthquake catalogues. The key hazard parameters used in this study include the earthquake magnitude, epicentral location, depth of hypocentre, and soil type. The epistemic errors in the estimation of the key hazard parameters are used in the randomization process.

2.2 Integration of Historical and Instrumental Seismicity

Historic earthquake catalogues are generally incomplete since the regional history (and geology) only provides information about large magnitude earthquakes, whereas small magnitude events are missing. Moreover, historical seismicity can play an important role in SHA as it may add information on seismic sources of a region that are not captured by instrumental records. However, before the instrumental seismicity can be accepted as being valid to predict future events in a new study region, it should be examined to ensure that it is consistent with the historical seismicity. For instance, Kythreoti (2002) investigated the seismicity of Cyprus and found that the instrumental seismicity was consistent with the historical seismicity of the studied region.

Figure 2 compares the magnitude-recurrence curves computed based on historical and instrumental catalogues for Pakistan, which is taken as a case study region in this article. It is shown that, contrary to Kythreoti's study, the seismic activity from the 13th to the 19th century does not compare well, and it underestimates the seismicity of the 20th century obtained from instrumental data. However, the underestimation is very likely to be due to the lack of historical data. This is partly supported by the presented data since the recurrence curves for the different centuries converge at the large magnitudes (M_w>7.0), at which historical data are known to provide more reliable information. Since the 20th century instrumental curve does not underestimate historical seismicity, it can be considered as a reasonable representation of the general seismicity of Pakistan. It should be mentioned that the instrumental seismicity only provides a view of a short time frame for the seismicity, which may not represent the long term seismic activity of a region at the meso-level. To generate reliable synthetic earthquake catalogues, it is thus necessary to include the historical seismicity. However, it should be borne in mind that historical seismicity is usually very limited and does not include small to moderate earthquakes. Indeed, whilst historical data are available for the past 2000 years in countries like Italy, Japan, China etc. (Mulargia et al., 2017), such data does not exist in many developing countries. The insufficiency of earthquake catalogues is a limitation in all existing methods, including the proposed ERA framework.

To combine historical and instrumental seismicities, either Bayesian statistics or methods like Kijko and Sellevoll's (1989) may be used. In this study, a simple approach which is easily incorporate into the code (and that can be improved in future studies) is proposed. Accordingly, the historical seismicity was integrated into the instrumental seismicity so that the recurrence pattern of the instrumental seismicity at the macro level remained unchanged. For this purpose, the available seismicity data for the study region was grouped into five magnitude ranges, as shown in Table 1. To generate a synthetic earthquake catalogue, for each magnitude range n^i_j earthquakes were randomly chosen out of $\sum n^i_j$ earthquakes; where i and j are century and magnitude range, respectively (see

Table 1). Based on this technique, the number of earthquake events in each magnitude range remains similar to that of the 20th century. This ensures that all the synthetic catalogues respect the recurrence relationship of the study region. The observation time window in the proposed PSHA method depends on the time span of the existing reliable instrumental data (usually 100 years). Note that the proposed method generates earthquakes at locations of historical events, even if events have not occurred in the last centuries. Therefore, spatial distribution of earthquakes covers areas of the 20th century and well before that. Note also that foreshocks and aftershocks are not removed in this study, which implies that the the generated catalogues may not strictly follow a Poissonian model. However, the initial screening removes events of non-significant consequence (PGA<0.05g), including most foreshocks and aftershocks. As a result, the events in these catalogues follow approximately a Poissonian model. It is to be noted that the Poissonian model does not predict rare events with large magnitude in active earthquake zones (Shende et al, 2009; Ben-Naim et al, 2013). Therefore, this ERA framework uses the screened catalogue as it is for generating the annual risk for the region. Moreover, ERA is significantly influenced by large magnitude events (as compared to low and moderate events) that are rare and do not necessary follow the Poissonian model. It should be also mentioned that the proposed ERA framework requires an annual frequency of exceedance (AFE) to calculate annual monetary and casualty risk. In this study, a PE of 10% in 50 years was selected to compare results of the proposed model with previous PSHA studies for the selected region (which only considered such PE, see next sections). However, the ERA can accommodate other PE values. The depth of the earthquakes considered in the calculation of PGAs ranges from 10 to 370 km. Finally, in this PSHA method, there is no need to assume earthquake recurrence relationships or to calculate maximum expected magnitude for the seismic sources. This can address some of the drawbacks associated with using conventional PSHA methods, as discussed earlier.

2.3 Seismic Sources

The PGA contours in small magnitude earthquakes (M_w<6) are expected to be nearly circular around their focal point due to the small rupture lengths, as shown schematically in Figure 3a (Kythreoti, 2002). Conversely, the PGA contours for strong earthquakes can be assumed as perpendicular to the rupture line. In a large magnitude event, the rupture line is usually oriented along existing fault lines (Wells and Coppersmith, 1994). For example, Figure 4 illustrates the spatial distribution of observed intensity for the Sichuan (2008) and the Chile (2010) earthquakes.

In this study, the focal point for new random events with large magnitudes (i.e. M_w>6) was placed within a distance equal to the expected error around the original epicentre, as described in the following section and shown in Figure 3b. From the epicentre of each new random event, an “Epicentral Fault Line” (EFL) was defined parallel to the general fault direction of the seismic source zone corresponding to the original seismic event. Seismic source zones were allocated using tectonic information on the direction and type (if known) of the main tectonic features.

Based on the magnitude of the earthquake event, the length of its corresponding EFL can be estimated using an appropriate fault length-magnitude relationship. In this study, the following relationships were adopted (Wells and Coppersmith, 1994):

$$\log(SLR) = -3.22 + 0.69M_w \tag{1}$$

$$\log(RLD) = -2.44 + 0.59M_w \tag{2}$$

where M_w is the moment magnitude of the earthquake; whereas *SLR* and *RLD* are the surface length and subsurface fault rupture length in kilometers (km), respectively. Accordingly, EFL was assumed to be the maximum of *SLR* and *RLD* calculated using the above equations.

It should be noted that to generate synthetic earthquake catalogues in the proposed method, the locations of the new seismic events were randomly placed within a circular area around the original focal point for small magnitude earthquakes (Figure 3a), or within an elliptical shape area around the original EFL for large magnitude earthquakes (Figure 3b). It should be also mentioned that, in many cases, systematic spatial variability of ground motion around seismic sources exists, thus inducing forward directivity effects that would modify the patterns shown in Figure 3 (Somerville *et al.,* 1997). Whilst this effect can be taken into account in

PSHA (Tothong *et al.,* 2007), the proposed model assumes the simple acceleration attenuation pattern shown in the figure. Therefore, further research should investigate ways of improving near-fault assessment.

Note that this ERA framework not only randomises the location of significant earthquakes over large distances (within rupture length on either side of the original epicentre), but it also replaces events with similar magnitude historical events that may be located farther from the replaced location (that too randomised over rupture length on either side of the original epicentres). This will give results significantly different from the "smoothed seismicity" approach. The authors have also adapted the framework to consider seismic gaps using a time-dependant approach (Mulyani, 2013), but this will be presented in future publications

2.4 Uncertainty in the Estimation of Key Hazard Parameters

In an attempt to quantify the epistemic errors in the key hazard parameters for the study region, available information on earthquake records (i.e. location, depth and magnitude of earthquakes) from different sources were collected and compared for the study region. By comparing existing earthquake catalogues in Pakistan, the mean error of the epicentral location of an earthquake was estimated as ±0.23 degrees (±25.4 km) for the instrumental seismicity (Khan, 2011; ISC, 2009). Figure 5a shows the distribution of calculated errors for location and magnitude of past earthquakes (1908 to 2008) in Pakistan. The calculated mean error in the epicentral location of earthquakes agrees well with previous research (Kagan, 2003) that found this error to be between 20 and 40 km, depending on the depth and magnitude of earthquakes.

Figure 5b shows the distribution of absolute errors in magnitude of the instrumental seismicity in Pakistan based on the existing earthquake catalogues. The results indicate that the mean error in magnitude determination of instrumental seismicity in Pakistan was around ±0.26 magnitude units (Khan, 2011).

It should be mentioned that in the proposed PSHA method, the magnitude of all earthquake events is expressed using the moment magnitude scale (M_w). However, the magnitude of some of the instrumental and historical earthquakes in Pakistan was measured using body-wave magnitude (M_b) or surface-wave magnitude (M_s). Therefore, the error in the conversion of the earthquake magnitude to M_w was another source of uncertainty (Kagan, 2003). Figure 6 shows the relationship between the measured M_w and its corresponding M_b and M_s for different recorded earthquakes in Pakistan and the surrounding region. Based on this information, the error of the conversion to M_w was ±0.24 and ±0.18 for M_b and M_s, respectively, with a 95% confidence level. Therefore, to convert the earthquake magnitudes to M_w the following equations were adopted:

$$M_W = 1.0092 M_b + 0.1341(\pm 0.24) \tag{3}$$

$$M_W = 0.6334 M_s + 2.2540(\pm 0.18) \tag{4}$$

For events not recorded in M_w, the effective mean error in the earthquake magnitude was calculated by using Square Root of the Sum of the Squares (SRSS) of the errors in the magnitude determination (i.e. ±0.26) and magnitude conversion (i.e. ±0.24 and ±0.18 for M_b and M_s, respectively). Likewise, the mean errors in the depth of hypocenters and the soil parameters required for attenuation relationships were considered to be 15% based on a sensitivity analysis carried out by Kythreoti (2002). The soil parameters were obtained from the geologic maps of the region. Whilst PSHA can be considered a site-specific analysis (McGuire, 2004) and therefore geological maps may not be adequate to provide comprehensive information for microzonation, this is often the only available information in many developing countries and therefore such maps are used in this study. Note also that the magnitude conversion relationships used here were derived from seismic data specific for the region under consideration. However, the proposed framework can accept more general conversion equations should the user consider magnitude conversion as epistemic uncertainty

Based on the above information, a significant number of random synthetic earthquake catalogues were generated to represent possible future events for a given period of time. Each synthetic catalogue contained all relevant events of the original instrumental catalogue, but their locations, magnitudes, and depths were modified according to their corresponding error values as discussed in previous paragraphs. To estimate the seismic hazard parameters for each new event in the synthetic catalogue, the following equation was used:

$$HP_R = HP_0 + (e \times N_R) \tag{5}$$

where HP_R and HP_0 are the new and original hazard parameters, respectively; e is the expected error for that specific hazard parameter, and N_R is a random number between -1 to 1 from a uniform distribution. Alternatively, more sophisticated distributions (such as normal distribution) can be used if they can be derived for a particular region. The current ERA study is carried out at union council level considering large areas. Whilst micro level soil variations are not considered in the calculations carried out in this study, the developed ERA framework can be used to perform risk studies at the micro level if the local soil data is available. The proposed PSHA method is general and flexible, and therefore, uncertainty in other hazard parameters (such as ground motion variability) can be easily incorporated in the calculations if deemed necessary. However, the procedure differs from conventional PSHA methods as the new catalogues are not generated from the recurrence relationship, but by assuming that recent seismicity (100 years) is representative of the general seismicity for small events. To respect the recurrence rates for each zone, compensation is made for known historical events.

3 DETERMINATION OF PGA

For all generated random events, an attenuation relationship was used to calculate the PGA level at the centre of each unit area considered for PSHA. In the case of Pakistan, this unit area (UA) was the 'Union Council' which is the smallest local administration unit. The results were then used to determine the PSHA map of the study region for the desired return period. The epicentral distance required to use this attenuation relationship was calculated from the geodetic coordinates of the epicentre (or nearest point on EFL) of the random event and the centre of each UA using the World Geodetic System (WGS) (Burke, 2003). The geodetic coordinate system WGS was incorporated into the PSHA framework, rather than a Cartesian coordinate system, to enable the study of much larger areas.

To determine the PGA in this study, Ambraseys *et al.* (2005) attenuation relationship was utilised as it incorporates the fault type and site soil specification without requiring detailed geological information. Figure 7 shows that the Ambraseys *et al.* (2005) attenuation relationship compares reasonably well with the recorded field data (Raghukant, 2008) and recorded PGA at Abbottabad (Javed *et al.,* 2006), Barotha, Maree and Tarbela (Burton and Cole, 2006) stations after the 2005 Kashmir earthquake in Pakistan. It should be mentioned that whilst Ambraseys et al. (2005) GMPE was used in this study, other recent equations (e.g. Akkar et al., 2014) or even a set of GMPEs can also be used in the proposed methodology. However, the use of Akkar et al. (2014) model in the calculations in this study is expected to change the hazard results in less than 10%. More sophisticated attenuation relationships can be easily incorporated in the proposed methodology as more information becomes available in the future.

In the proposed PSHA method, the inclusion of earthquake events in the catalogue uses a minimum PGA at a UA rather than the earthquake magnitude. The minimum PGA that can cause damage depends on the vulnerability of the building stock in the area (in this study, the damage ratio was around 3% for the minimum PGA). Therefore, unlike conventional PSHA methods, no lower bound magnitude 'cutoff point' needs to be considered. The proposed methodology is also independent of the selected seismic area sources, as new events are smeared around their original location, and the seismic source zones are used only to determine the general fault orientation. Whilst the selection of seismic source zones in this method is based on the direction and type of existing faults, other information can be included if required by the attenuation relationship.

4 EARTHQUAKE RISK ASSESSMENT MODEL (EQRAM)

The proposed PSHA methodology was incorporated into an ERA framework called EarthQuake Risk

Assessment Model (EQRAM). Figure 8 shows the three modules of the EQRAM programme: 1) PSHA, 2) vulnerability assessment and 3) risk assessment. The first module was discussed in detail in the previous sections 2 and 3, whereas the vulnerability module is the relationship (or relationships) between damage and ground shaking levels. EQRAM uses vulnerability relationships correlating mean damage ratio (MDR) to PGA. Vulnerability assessment is a complicated process as the existing building stock in the majority of the developing countries is mostly non-engineered with weak materials and poor construction practices. Comprehensive data on damage from past earthquakes are in general not available in developing countries. However, if applied at the macro scale level, basic vulnerability relationships can give reasonable results (Kythreoti, 2002). In this study, a general framework for determining the vulnerability of structures in developing countries (Ahmad *et al.,* 2015) was used to provide input data for the vulnerability module of EQRAM.

The third module of EQRAM addresses risk and casualty assessments. In the case of casualty risk calculation, casualty models are required either as simple relationships such as mean fatality/injury ratios against PGA or more advanced models such as Coburn and Spence (1992) model. EQRAM uses the Coburn and Spence (1992) model which takes into account multiple parameters such as building damage, population occupancy trends, number of entrapped occupants and rescue capability at various levels. The third module of EQRAM also includes the building inventory (and population) assessment. A simple and low cost methodology was developed and used in EQRAM for building inventory assessments. EQRAM is based on a geographic information system using proprietary software (Zeiler, 1999; Burke, 2003), which facilitates the incorporation of the spatial aspects of hazard and risk. The probability or likelihood of damage and consequent loss of elements at risk can be calculated from the results of module 3.

Using results from the PSHA (module 1), appropriate vulnerability relationships (module 2), and casualty models, EQRAM calculates building damage and casualty risks (module 3). The subsequent sections described how EQRAM was used to carry out PSHA for Pakistan and arrive at risk assessment information for a region in Pakistan.

5 SEISMOTECTONICS AND SOURCE ZONING DATA FOR PAKISTAN

The geomorphology of Pakistan (area=796,095 km^2) varies from the high mountains of Himalayas, Hindukush, Karakorum and Pamirs in the north to the coastline of the Arabian Sea in the south. Pakistan is situated on the western-rifted margin of the Indo-Pakistan sub-continental plate and lies on the northwestern corner of the Indian lithospheric plate, the southern part of the Afghan craton, and the northern part of the Arabian oceanic subducting plate (Zaigham and Mallick, 2000). The Indian plate has been in collision with the Eurasian plate for more than 35 million years, and it is still moving with a velocity of approximately 40 mm/year (PMD-NORSAR 2007). This high rate of movement is the cause of the high seismicity of the region as well as of the high mountain ranges. Figure 9 shows the seismic activity around the Indian plate boundaries between 1973 and 2008 (ISC, 2009). The major tectonic features of Pakistan and surrounding areas are shown in Figure 10 based on the information provided by BCP (2007). The major fault zones in Pakistan include the Sulaiman stretch in transpression and the Himalayan zone under-thrusting the Eurasian plate (Jadoon, 1992). Based on the studies of Pakistan Meteorological Department (PMD-NORSAR, 2007), Pakistan and its surrounding regions were divided into 19 seismic zones by considering the direction of movement of the region, source mechanism of the fault system, and seismic activity and geology of the region (see Figure 11). It should be noted that whilst the source mechanism is not amongst the key parameters randomized in the proposed methodology, this information is used as an input. The tectonic characteristics of these seismic zones are listed in Table 2. For each seismic zone, the general fault direction was determined on the basis of existing faults within each seismic zone.

6 PSHA FOR PAKISTAN

To implement the proposed PSHA methodology, historical seismicity information of Pakistan was collected from the PMD-NORSAR (2007) historical database that includes seismic events from 25 AD (Taxila earthquake) and up to 1905 (Kangra earthquake), as shown in Figure 12. The historical data show that major earthquakes cluster in the north east of the study region, as well as in the centre of Pakistan near Quetta (where an earthquake occurred in 2008). Some of the important historic seismic events in Pakistan are listed in Table 3.

An instrumental earthquake catalogue ranging from 20°N to 38°N and 50°E to 85°E was obtained from the UK International Seismological Centre (ISC, 2009). Instrumental seismological data for Pakistan were recorded since 1960, and thus the instrumental seismic data are limited to the past half century. The area included in the instrumental catalogue is much extensive than the area of Pakistan so as to include all earthquakes that are likely to impact Pakistan. These data are filtered to eliminate events with no impact (PGA<0.05g) to make the catalogue compact. These data are merged into a single catalogue as explained earlier to maintain the recurrence relationship at the macro level.

The selected instrumental and historical seismicity data (for Pakistan) categorized into different magnitude ranges are shown in Table 4. Synthetic earthquake catalogues are then generated by randomizing the key hazard parameters as explained previously in Section 2.2. Based on the sensitivity analysis, a minimum number of 50 simulations (synthetic earthquake catalogues) is recommended to lead to an adequate estimation of seismic hazard for the case study region (Khan, 2010). However, the results presented in this study are based on 100 synthetic earthquake catalogues.

The Ambraseys *et al.* (2005) attenuation relationship (Equation 6) was used to calculate the PGA for each event at each UA region of Pakistan.

$$\log(a) = 2.522 - 0.142M_W - (3.184 - 0.314M_W)log\sqrt{(d^2 + 7.6^2)} + 0.137S_S + 0.05S_A - 0.084F_N + 0.062F_T - 0.044F_O \quad (6)$$

where d is the epicentral distance; S_S=1 for soft soil (0 otherwise); S_A=1 for stiff soil (0 otherwise); F_N=1 for normal fault (0 otherwise); F_T=1 for thrust fault (0 otherwise); and F_O=1 for other faulting (0 otherwise). If the soil is not strictly stiff or soft based on the soil classification, the values of S_S and S_A can be chosen between 0 and 1 (Kythreoti, 2002). Note that the proposed method is different from traditional event by event calculation methods and therefore ground motion scatter is not explicitly considered in Equation 6. However, the ERA framework can accommodate for any type of ground motion relationship, with (or without) prescribed scatter.

It should be noted that due to the non-linear nature of equation 6 ignoring the ground-motion scatter (σ) may lead to underestimated ground accelerations. Results indicate that the maximum and the average of the calculated PGA levels (POE of 10% in 50 years) for the case study example will increase by maximum 5% and 1%, respectively, if σ is included in the calculations. Therefore, ignoring this factor does not considerably affect the predicted results.

The geological information for each UA was obtained using Pakistan's Geological Survey map (GSP, 2009), as well as from information provided by Hayat (2003) and data obtained from the National Highway Authority (NHA 2009). The calculated PGAs are then used to obtain Probabilistic Seismic Hazard maps for the region with a 10% Probability of Exceedance (POE) in 50 years as shown in Figure 13. It should be noted that the number of simulations are kept to 100 as less than 500 years return period assessments are usually required for ERA of residential buildings. This in turn also reduces computational time.

Figure 14 compares the calculated hazard map (Figure 13) with the existing hazard maps produced by the Building Code of Pakistan (BCP, 2007), Geological Survey of Pakistan (GSP, 2006), Pakistan Meteorological Department (PMD-NORSAR, 2007), and Global Seismic Hazard Assessment Program (GSHAP) developed by the US Geological Survey (USGS, 2009). It should be noted that the GSP map was updated after the Kashmir (2005) earthquake, but the new map was based on the old 1974 GSP map and was not developed using a PSHA approach. Whilst the PMD (PMD-NORSAR, 2007) and BCP (BCP, 2007) maps were both developed by using PSHA studies, they still show different results as they are based on different seismic zonation maps. Since the BCP map is derived from the latest study, it appears to give the better results. The GSHAP map is part of the global hazard assessment programme carried out at the global scale by USGS (2009), and does not present local seismic hazard distribution for the case study region in Pakistan.

The results of this study indicate that, despite some differences, in general there is a good agreement between the seismic hazard assessment carried out by the proposed methodology and the existing seismic hazard maps of Pakistan. Figure 15 compares the ratio of areas exceeding a specific PGA level for the different hazard maps. It can be seen that, overall, the map by the Pakistan Meteorological Department (PMD-NORSAR, 2007) gives the highest PGA levels, whereas that by the Geological Survey of Pakistan (GSP, 2006) gives the lowest. Note that the latest PSHA method adopted by PMD-NORSAR places Peshawar at PGA=0.3g. However, Ali and Khan (2005) provided a critical review of seismic hazard zoning of Peshawar city, suggesting that PGA should not be above 0.15g. This indicates that the existing PSHA methods can overestimate hazard. This will increase the perceived risk, in turn increasing the cost of any mitigation measures.

It is also shown that the seismic hazard map calculated using the proposed PSHA methodology compares well with that included in the Building Code of Pakistan (BCP, 2007). However, the results of the current study lead to a more detailed local seismic hazard distribution while using only limited publicly available seismo-tectonic information.

7 SEISMIC RISK ASSESSMENT FOR THE REGION OF ISLAMABAD TO PESHAWAR

To demonstrate the use of EQRAM, a study region between Islamabad and Peshawar was selected to carry out ERA.

- Data on earthquake catalogue and seismic zoning is input for the study region. EQRAM automatically reduces it by removing events of lesser consequence.
- As input, EQRAM also requires soil types for use in the Ambraseys' (2005) GMPE. Figure 16 shows the topographic and soil topology map of the study region. The different soil types and corresponding S_S and S_A values are given in Table 5. As it can be seen, since the seven types of soil found in the region cannot be strictly classified as rock, stiff or soft soil, the values S_S and S_A are kept between 0 and 1 for calculations (Kythreoti, 2002).
- The EQRAM PSHA module was also used to determine the local seismic hazard map for the study region with a 10% POE in 50 years (Figure 17a).
- The building inventory was developed for the case study region by using 1998 census data (FBS ,2007) and satellite imagery (Khan, 2010). This is input to EQRAM.
- Initially, basic vulnerability curves from GESI (GESI 2001) were used. A further study at the University of Sheffield (Ahmad *et al.,* 2015) has recently produced new vulnerability curves for the typical RC structures in the region, and these curves will be adopted in future studies (input to EQRAM).
- Reconstruction costs for each category of buildings were also obtained from local engineers based on the Net Present Value (NPV) of 2008. This is also input with the corresponding vulnerability curves.
- EQRAM produced the monetary risk assessment for the study region, as shown in Figure 17b. The monetary risk was also converted into insurance premium. It should be noted that the reported risk in Figure 17b is the average annual risk within the considered timeframe.
- EQRAM also includes a casualty module, which details can be found in Khan (2010). To demonstrate the use of this module, Figure 18a and b show the likely annual fatality and annual injury results for the study region, respectively.
- As expected, most casualty risk is concentrated in and around the large urban areas of Peshawar and Islamabad.

It should be finally noted that the present study is part of a wider project on earthquake risk mitigation framework for developing countries currently underway at the University of Sheffield. The completed EQRAM programme will include additional components for tsunamis, landslides, industrial facilities, services, and optimum risk mitigation strategies.

8 CONCLUSIONS

A practical PSHA methodology is proposed for integrating with a new ERA framework (EQRAM) for countries where limited studies on tectonics and seismicity exist. This PHSA method is based on synthetic earthquake catalogues that are generated by randomizing the key hazard parameters of earthquake magnitude, epicentral location, depth of hypocentre, and basic tectonic and geological parameters. Existing historical seismicity data are integrated with the more complete instrumental seismicity in such a way that the recurrence pattern of the instrumental seismicity remains unchanged. The method is demonstrated by carrying out a PSHA study for Pakistan. The PSHA results compare well with previous PSHA studies. In particular, the results are consistent with the PSHA map included in the most recent National Building Code of Pakistan. This indicates that the proposed method can be suitable for generating hazard maps in regions where limited data are available. EQRAM, which integrates the PSHA method, was then used to generate ERA for a selected region between Islamabad and Peshawar. As expected, most casualty risk is concentrated in and around the large urban areas of Peshawar and Islamabad. The proposed framework can be extended to other developing regions around the world and its results can be used to assist relevant stakeholders and decision-makers on preparedness, emergency response and mitigation actions.

REFERENCES

Abrahamson Norman A (2000), "State of the Practice of Seismic Hazard Evaluation," *Proceedings of the CeoEng2000 conference*, Melbourne, Australia, 19-24 November.

Abrahamson Norman A (2006), "Seismic Hazard Assessment: Problems with Current Practice and Future Developments," *Proceedings of the 1st European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland (in CD).

Ahmad Soheib, Khan Shaukat Ali, Pilakoutas Kypros and Khan Qaiser Uz Zaman (2015), "Empirical Vulnerability Assessment of the Non-Engineered Reinforced Concrete Structures using the Kashmir Earthquake Damage Data", *Bulletin of Earthquake Engineering*, **13**(9), 2611-2628.

Algermissen Sylvester Theodore and Perkins David M (1972), "A Technique for Seismic Zoning—General Considerations and Parameters," *Proceedings of the 1st International Conference on Microzonation*, Seattle, Washington, 865–878.

Ali Qaisar and Khan Akhtar Naeem (2005), "A Critical Review of the Seismic Hazard Zoning of Peshawar and Adjoining Areas," *Journal of Earthquake Engineering*, **9**(05), 587-607.

Ambraseys Nicholas Neocles, Douglas John, Sarma Sarada K and Smith Patrick M (2005), "Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Horizontal Peak Ground Acceleration and, Spectral Acceleration," *Bulletin of Earthquake Engineering*, **3**(1), 1-53.

Assatourians Karen and Atkinson Gail M (2013), "EqHaz: An Open-Source Probabilistic Seismic-Hazard Code Based on the Monte Carlo Simulation Approach," *Seismological Research Letters*, **84**(3), 516-524.

BCP-Building Code of Pakistan (2007) Building Code of Pakistan Seismic Provisions (SP-2007), Ministry of Housing and Works, Government of Pakistan, Islamabad.

Beauval Celine, Scotti Oona and Bonilla Fabian (2006), "The Role of Seismicity Models in Probabilistic Seismic Hazard Estimation: Comparison of a Zoning and a Smoothing approach," *Geophysical Journal International*, **165**(2), 584-595.

Bender Bernic and Perkins David M (1987), SEISRISK III: A Computer Program for Seismic Hazard Estimation, USGS Bulletin 1772, US Government Printing Office, Washington.

Ben-Naim Eli, Daub Eric G and Johnson Paul A (2013), "Recurrence Statistics of Great Earthquakes", Geophysical Research Letters, 40(12), 3021-3025.

Bommer Julian J (2002), "Deterministic vs. Probabilistic Seismic Hazard Assessment: an Exaggerated and Obstructive Dichotomy," *Journal of Earthquake Engineering*, **6**(spec01), 43-73.

Bommer Jualian J and Scherbaum Frank (2008), “The Use and Misuse of Logic Trees in Probabilistic Seismic Hazard analysis,” *Earthquake Spectra*, **24**(4), 997-1009.

Burke Robert (2003), Getting to know ArcObjects: Programming ArcGIS with VBA. Environmental Systems Research Institute, Inc., Redlands, CA, USA.

Burton Paul and Cole Simon W (2006), "Pakistan Earthquake 2005 October 8: Earthquake Expectation and Seismic Hazard Through to Impact," *Proceedings of the 1st European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland (in CD).

Coburn Andrew and Spence Robin (1992), Earthquake Protection, John Wiley and Sons Ltd., Chichester, UK.

Cornell C Allin (1968), "Engineering Seismic Risk Analysis," *Bulletin of the Seismological Society of America*, **58**(5), 1583-1606.

Cornell C Allin (1971), "Probabilistic Analysis of Damage to Structures under Seismic Loads," in Howells, D.A., Haigh, I.P., and Taylor, C. (editors), Dynamic Waves in Civil Engineering, New York, Wiley-Interscience, 473–493.

Cornell C Allin and Vanmarcke Erik H (1969), "The Major Influences on Seismic Risk," *Proceedings of the 4th World Conference on Earthquake Engineering*, Santiago, Chile, Vol. 1, 69–83.

Crowley Helen and Bommer Julian J (2006), "Modelling Seismic Hazard in Earthquake Loss Models with Spatially Distributed Exposure”, *Bulletin of Earthquake Engineering*, **4**(3), 249-273.

Der Kiureghian Armen and Ang Andrew H (1977), “A Fault-Rupture Model for Seismic Risk Analysis”, *Bulletin of the Seismological Society of America*, **67**(4), 1173-1194.

FBS-Federal Bureau of Statistics (2007), Government of Pakistan, Islamabad, Pakistan, at http://www.statpak.gov.pk/depts/index.html (Accessed on 9th December 2007).

Field Edward H, Jordan Thomas H and Cornell C Allin (2003), “OpenSHA: A Developing Community-Modeling Environment for Seismic Hazard Analysis”, *Seismological Research Letters*, **74**(4), 406-419.

GEM (2011), Global Earthquake Model, https://www.globalquakemodel.org/

GESI (2001), Global Earthquake Safety Initiative, Pilot Project, GeoHazards International (GHI), United Nations Centre for Regional Development, Final Report, June 2001.

GSP (Geological Survey of Pakistan (GSP) (2006) Seismic Hazard Map of Pakistan, Geological Survey of Pakistan, Government of Islamic Republic of Pakistan, Islamabad, Pakistan.

GSP (Geological Survey of Pakistan) Geological Survey of Pakistan (GSP) (2009) Seismic Hazard Map of Pakistan, Geological Survey of Pakistan, Ministry of Petroleum and Natural Resources, Islamabad, Pakistan.

Hanks Thomas C, and Cornell C Allin (1994) "Probabilistic Seismic Hazard Analysis: A Beginner's Guide," *Proceedings of the 5th Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping*, North Carolina State University, Raleigh, USA.

Hayat Khizar (2003) "Geotechnical Zonation and Their Relation to Geology of Pakistan," PhD Thesis, Institute of Geology, University of the Punjab, Lahore, Pakistan.

ISC (2009) International Seismological Centre Pipers Lane, Thatcham, Berkshire, RG19 4NS, UK, at http://www.isc.ac.uk/

Jadoon Ishtiaq AK (1992), "Ocean/continental Transitional Crust Underneath the Sulaiman Thrust Lobe and an Evolutionary Tectonic Model for the Indian/Afghan Collision Zone," *Pakistan Journal of Hydrocarbon Research*, **4**(2), 33-45.

Javed Mohammad, Khan Akhtar Naeem, Penna Andrea and Magenes Guido (2006), "Behaviour of Masonry Structures During the Kashmir 2005 Earthquake," *Proceedings of the 1st European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland.

Kagan Yan Y (2003), "Accuracy of Modern Global Earthquake Catalogs", *Physics of the Earth and Planetary Interiors*, **135**(2), 173-209.

Khan Shaukat Ali (2011), "An Earthquake Risk Assessment Framework for Developing Countries: Pakistan Case Study," PhD Thesis, Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK.

Kijko Andrzej and Sellevoll Markvard A (1989), “Estimation of Earthquake Hazard Parameters from Incomplete Data Files. Part I. Utilization of Extreme and Complete Catalogs with Different Threshold Magnitudes,” *Bulletin of the Seismological Society of America*, **79**(3), 645-654.

Krinitzsky Ellis L (1993), "Earthquake Probability in Engineering: Part 1. The Use and Misuse of Expert Opinion," *Engineering Geology*, **33**(4), 257-288.

Krinitzsky Ellis L (2003), "How to Combine Deterministic and Probabilistic Methods for Assessing Earthquake Hazards," *Engineering. Geology*, **70**(1), 157–163.

Kythreoti Stella (2002), "Earthquake Risk Assessment and Management Case Study: Cyprus," PhD Thesis, Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK.

McGuire Robin K (2004), Seismic Hazard and Risk Analysis. Earthquake Engineering Research Institute, MNO-10, Oakland, CA, USA.

McGuire Robin K (1976), FORTRAN Computer Program for Seismic Risk Calculations, USGS Open-File Report 76-67.

McGuire Robin K (1993), "Computations of Seismic Hazard," in Giardini D and Basham PW (editors), Global Seismic Hazard Assessment Program, *Annals of Geophysics*, **34**, 181-200.

McGuire Robin K (2001), "Deterministic vs. probabilistic earthquake hazards and risks," *Soil Dynamics and Earthquake Engineering.,* **21**, 377-384.

Mulargia Francesco, Stark Philip B and Geller Robert J (2017), "Why is Probabilistic Seismic Hazard Analysis (PSHA) still used?," *Physics of the Earth and Planetary Interiors*, **264**(March 2017), 63-75.

Mulyani Rini (2013) Extended Framework for Earthquake and Tsunami Risk Assessment: Padang City as a case study, PhD thesis, Dept. of Civil & Structural Engineering, The University of Sheffield, UK.

Musson Roger MW (1999), "Probabilistic Seismic Hazard Maps for the North Balkan Region," *Annals of Geophysics*, **42**(6), 1109-1124.

Musson Roger MW (2000), "Generalised Seismic Hazard Maps for the Pannonian Basin Using Probabilistic Methods," *Pure and Applied Geophysics*, **157**(1-2), 147–169.

NHA (2009), National Highway Authority, NHA HQ, 27, Mauve Area, G-9/1, Islamabad, Pakistan.

NHSM-National Seismic Hazard Maps (2008), United States Geological Survey, Open-File Report, 2008–1128.

Oliveira Carlos Sousa and Campos Costa Alfredo (2006), "Overview on Earthquake Hazard Assessment - Methods and New Trends", in Oliveira CS, Roca A and Goula A (editors) "Assessing and Managing Earthquake Risk", Springer, 15-46

Ordaz Mario, Aguilar Armando and Arboleda Jose (2003), Crisis 2003 Ver. 3.01, Program for Computing Seismic Hazard. Available at http://www.iingen.unam.mx.

PMD-NORSAR (2007) Seismic Hazard Analysis and Zonation for Pakistan, Azad Jammu and Kashmir, A Report by: Pakistan Meteorological Department (PMD) and NORSAR-Norway, Islamabad, Pakistan.

Raghu Kanth STG (2008), "Ground Motion Estimation During the Kashmir Earthquake of 8th October 2005," *Natural Hazards*, **46**(1), 1–13.

RE (2009). Risk Engineering Inc. Website http://www.riskeng.com/ (Accessed on 12th March 2009).

Reiter Leon (1990) "Earthquake Hazard Analysis: Issues and Insights," Columbia University Press, New York, USA.

Robinson D and Fulford G (2005), EQRM: Geoscience Australia's Earthquake Risk Model Technical Manual, Version 3.0, GA Record 2005/01, Geoscience Australia, Canberra.

Shapira Avi (1983), "Potential Earthquake Risk Estimations by Application of a Simulation Process," *Tectonophysics*, **95**(1), 75-89.

Shende VJ, Ramakrishna TVS and Gupta ID (2009), "A non-Poissonian recurrence model for large magnitude earthquakes in Central Himalayan region", ACSGE-2009, Oct 25-27, BITS Pilani, India.

Sokolov Vladmir, Wenzel Friedemann, Mohindra Rakesh, Grecu Bogdan and Radulian Mircea (2007), "Probabilistic Seismic Hazard Assessment for Romania Considering Intermediate-depth (Vrancea) and Shallow (Crustal) Seismicity," *Proceedings of the Int. Symposium on Strong Vrancea Earthquake and Risk Mitigation*, Bucharest, Romania.

Somerville Paul G, Smith Nancy F, Graves Robert W and Abrahamson Norman A (1997), "Modification of Empirical Strong Motion Attenuation Relations to Include the Amplitude and Duration Effect of Rupture Directivity," *Seismological Research Letters*, **68**(1), 199-222.

Thenhaus Paul C and Campbell Kenneth W (2003), "Seismic Hazard Analysis," in: W.-F. Chen and C. Scawthorn (editors), Earthquake Engineering Handbook, CRC Press, Boca Raton, FL, 8-1 to 50.

Tothong Polsak, Cornell C Allin, Baker JW. (2007) "Explicit Directivity-Pulse Inclusion in Probabilistic

Seismic Hazard Analysis," *Earthquake Spectra*, **23**(4), 867-891.
USGS (2008), Seismic Hazard of Pakistan, at: http://earthquake.usgs.gov/earthquakes/world/pakistan/gshap.php
USGS (2009), United States Geological Survey, Earthquake Hazard Program, at http://earthquake.usgs.gov/
Wells Donald L and Coppersmith Kevin J (1994), "New Empirical Relationships Among Magnitude, Rupture Length, Rupture Width, and Surface Displacements," *Bulletin of the Seismological Society of America*, **84**(4), 974-1002.
Woo Gordon (1996), "Kernel Estimation Methods for Seismic Hazard Area Source Modeling," *Bulletin of the Seismological Society of America*, **86**(2), 353-362.Zabukovec B, Motnikar BS and Zupbancic P (2000), OHAZ: A Computer Program for Seismic Hazard Calculation, User Manual, Geophysical Survey of Slovenia, Ljubljana.
Zaigham Nayyer Alam and Mallick Khalil Ahmed (2000), "Bela Ophiolite Zone of Southern Pakistan: Tectonic Setting and Associated Mineral Deposits," *GSA Bulletin*, **112**(3), 478-89.
Zeiler Michael (1999), Modeling Our World: The ESRI Guide to Geodatabase Design, Environmental Systems Research Institute (ESRI), Redlands, CA, USA.

FIGURES

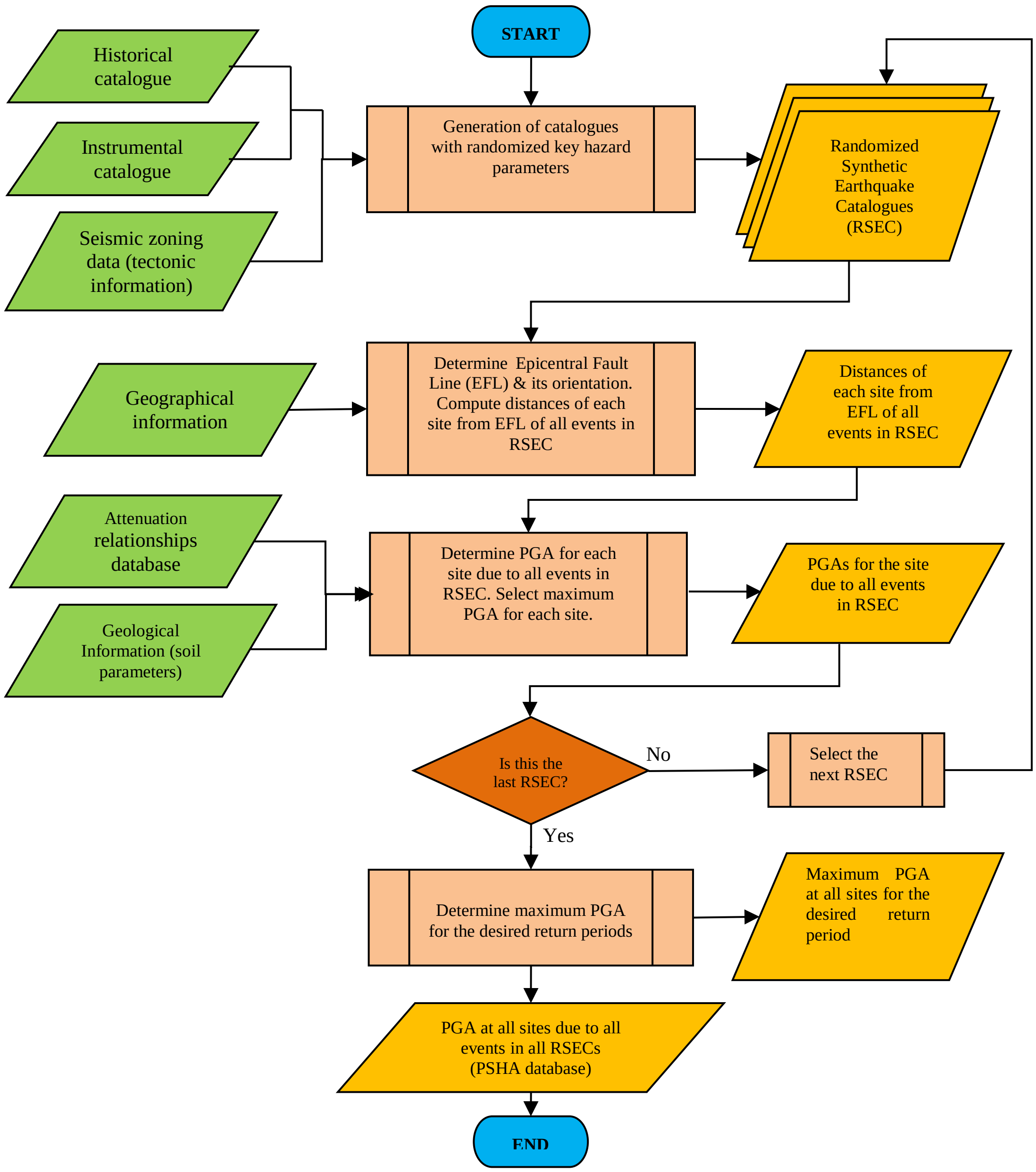


Figure 1. Flowchart of the proposed PSHA process

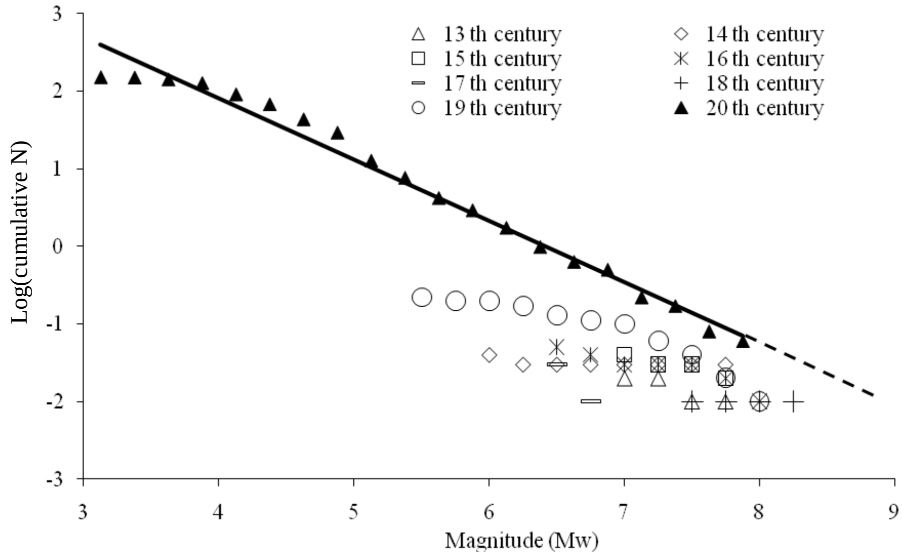
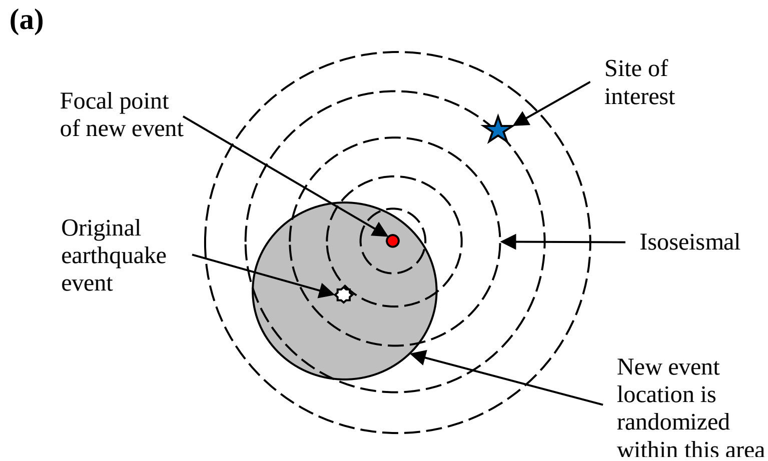


Figure 2. Magnitude-recurrence relations computed with the data from historical and instrumental catalogues in different centuries for the study region in Pakistan



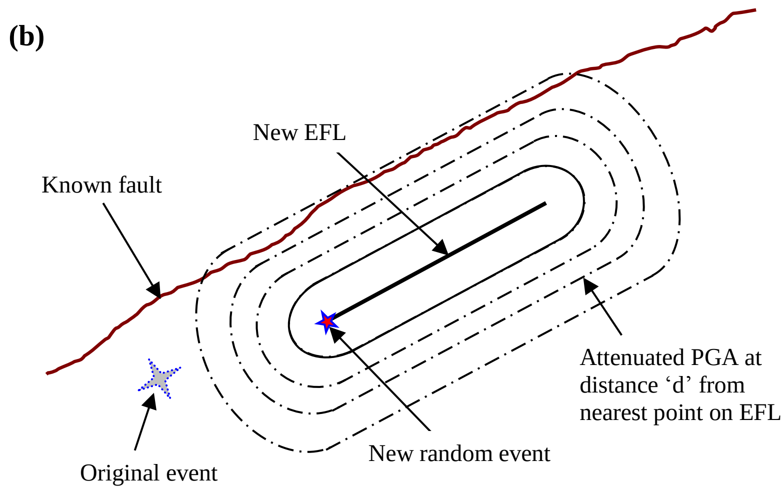


Figure 3. Generation of new random event and earthquake intensity (a) spreading from focal point, and (b) spreading from the rupture line (EFL)

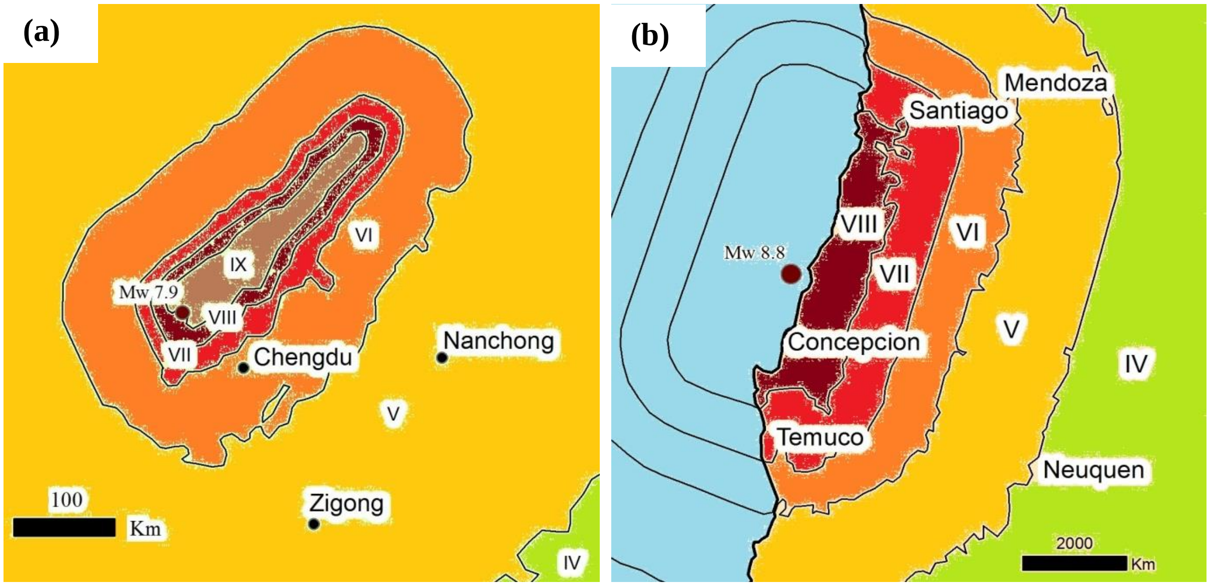
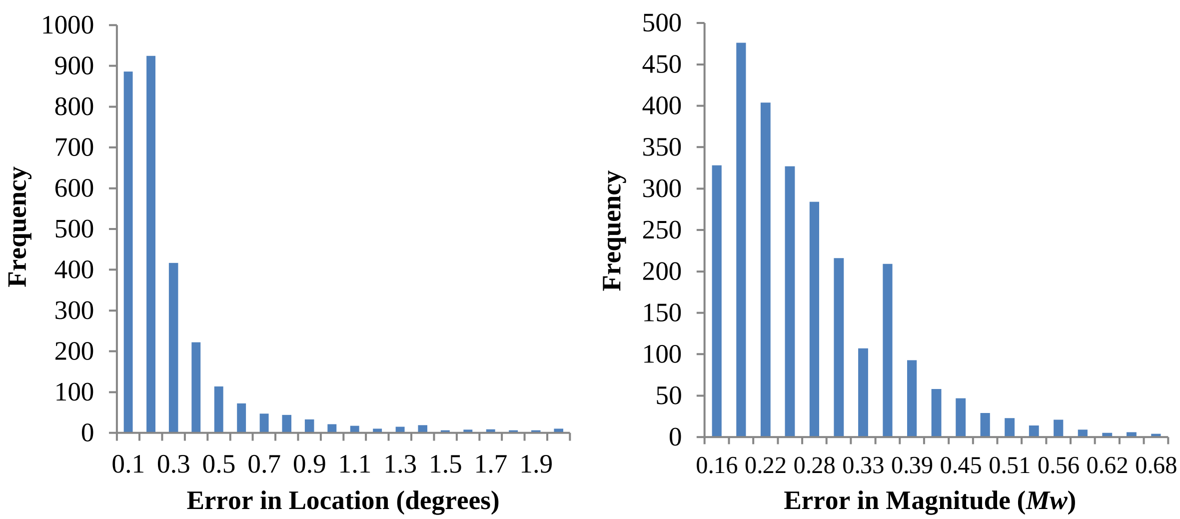


Figure 4. Estimated earthquake intensity patterns for (a) Chengdu in China (2008) and (b) Concepcion in Chile (2010) adopted from USGS website (USGS, 2010)



(a) (b)

Figure 5. Distribution of errors in the determination of (a) location and (b) magnitude of instrumental seismicity in Pakistan

(a)

(b)

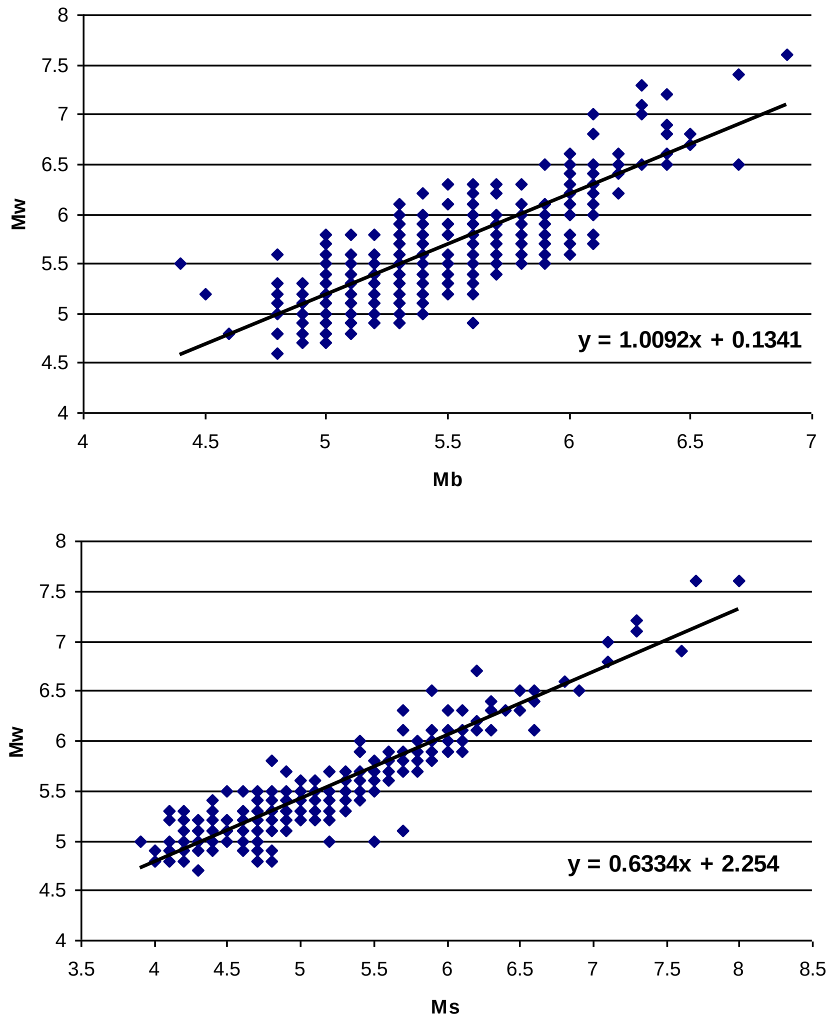


Figure 6. Conversion of (a) M_b into M_w, (b) M_s into M_w

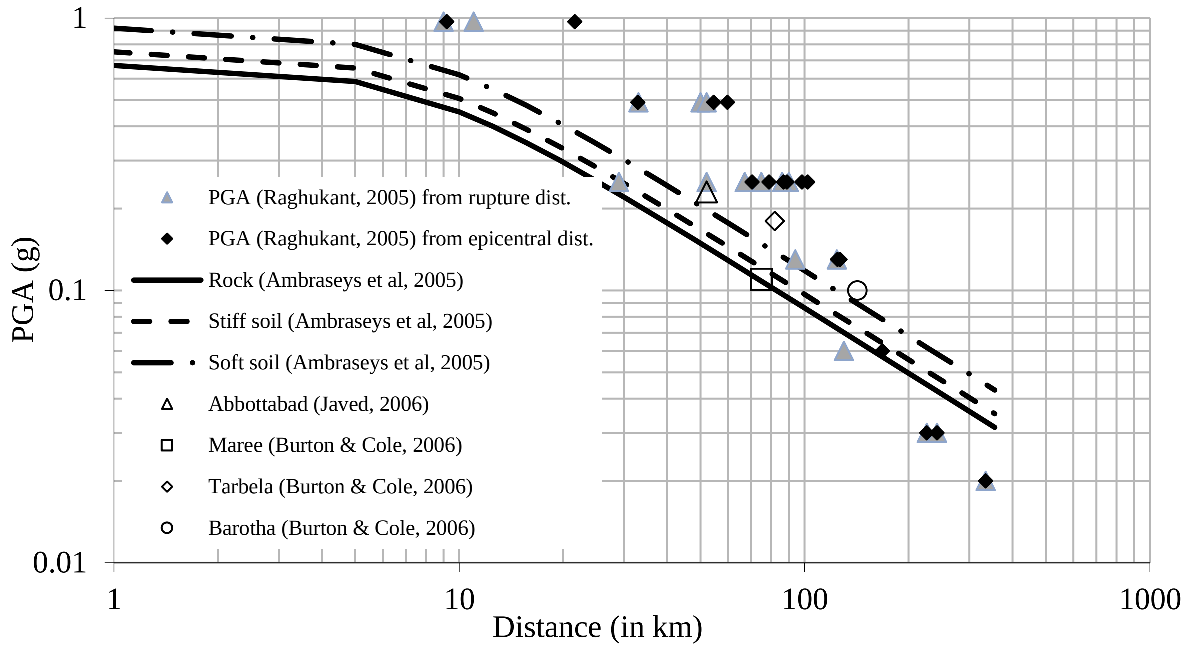


Figure 7. Comparison between Ambraseys *et al.,* (2005) attenuation relationship with the observed PGA recorded after 2005 Kashmir earthquake

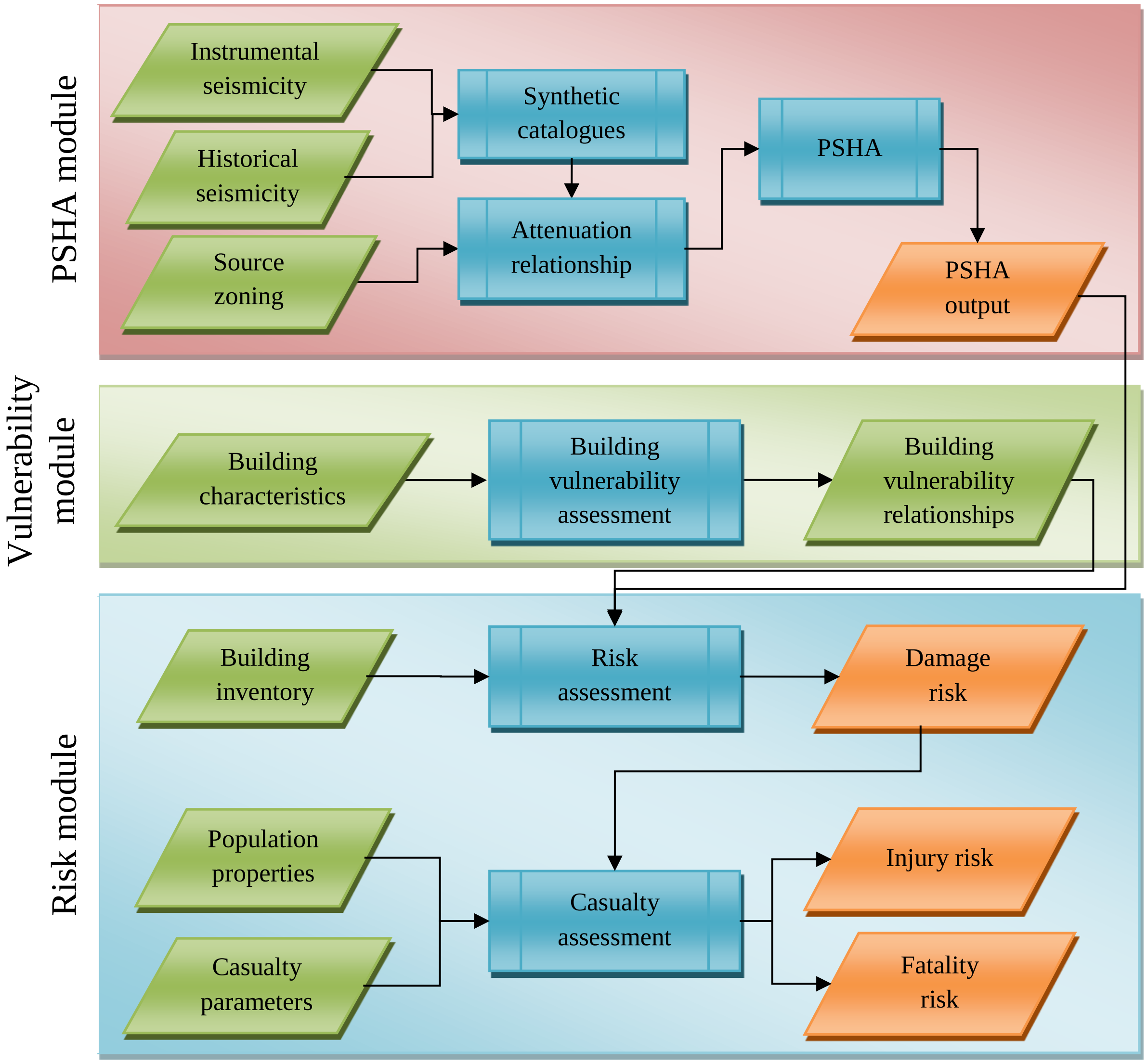


Figure 8. General outline of the EQRAM programme

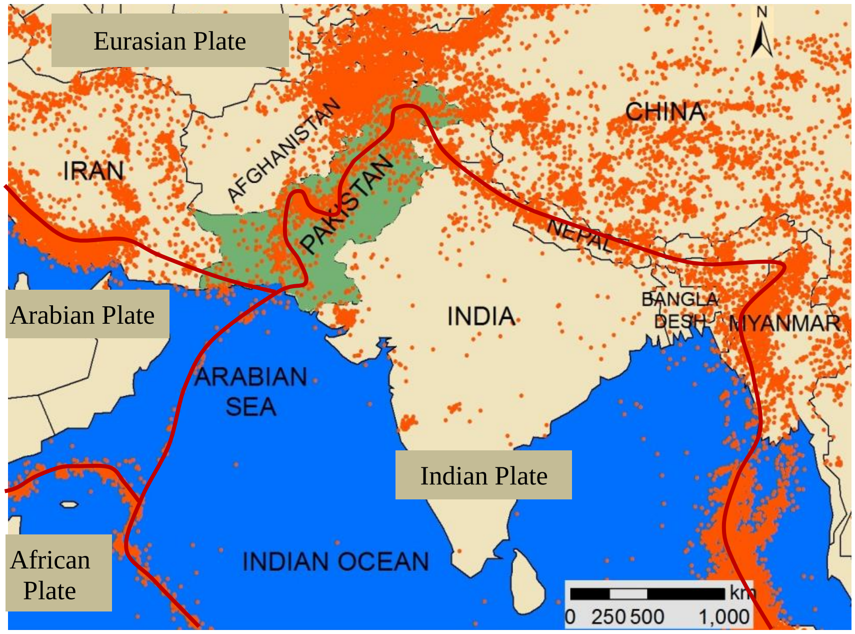


Figure 9. Seismic activity around the Indian plate boundaries between 1973 and 2008 (after ISC, 2009)

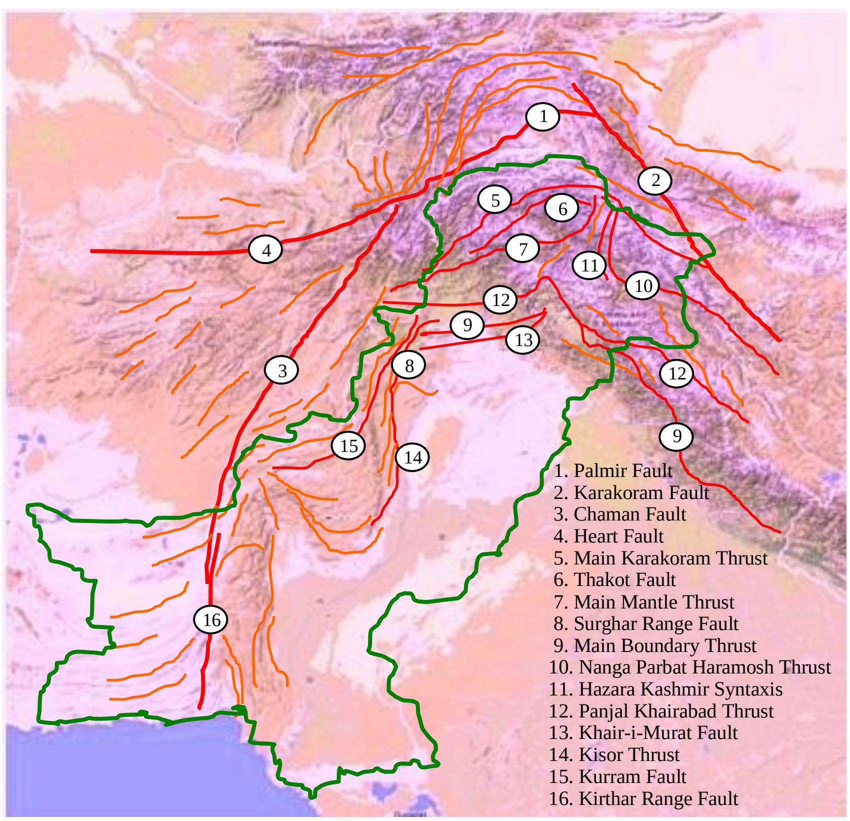


Figure 10. Major tectonic features in Pakistan (after BCP, 2007)

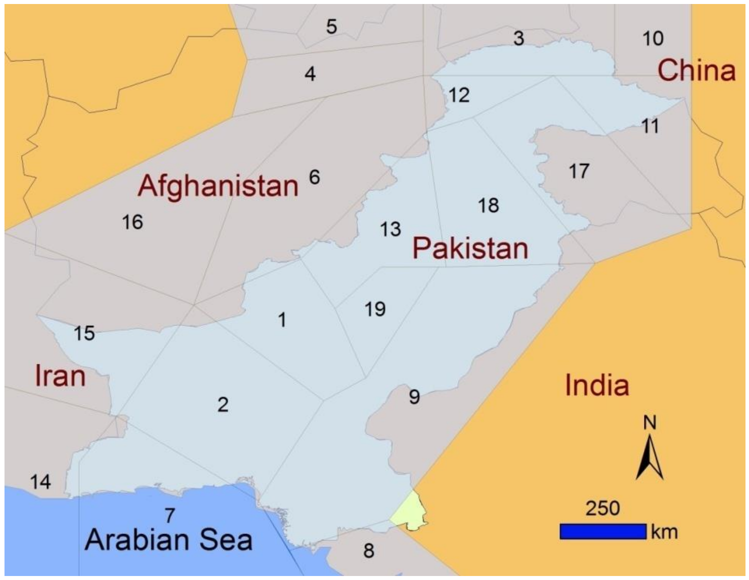


Figure 11. Seismic source zoning of Pakistan region (after PMD-NORSAR, 2007)

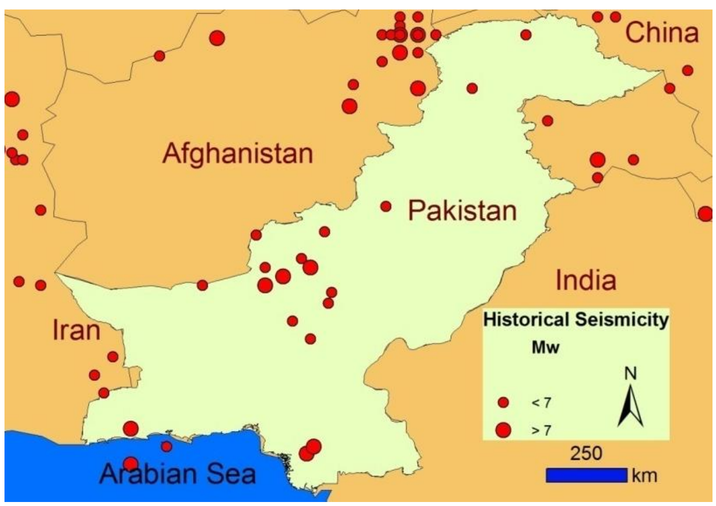


Figure 12. Major historical earthquakes from the PMD-NORSAR catalogue (25-1905 AD)

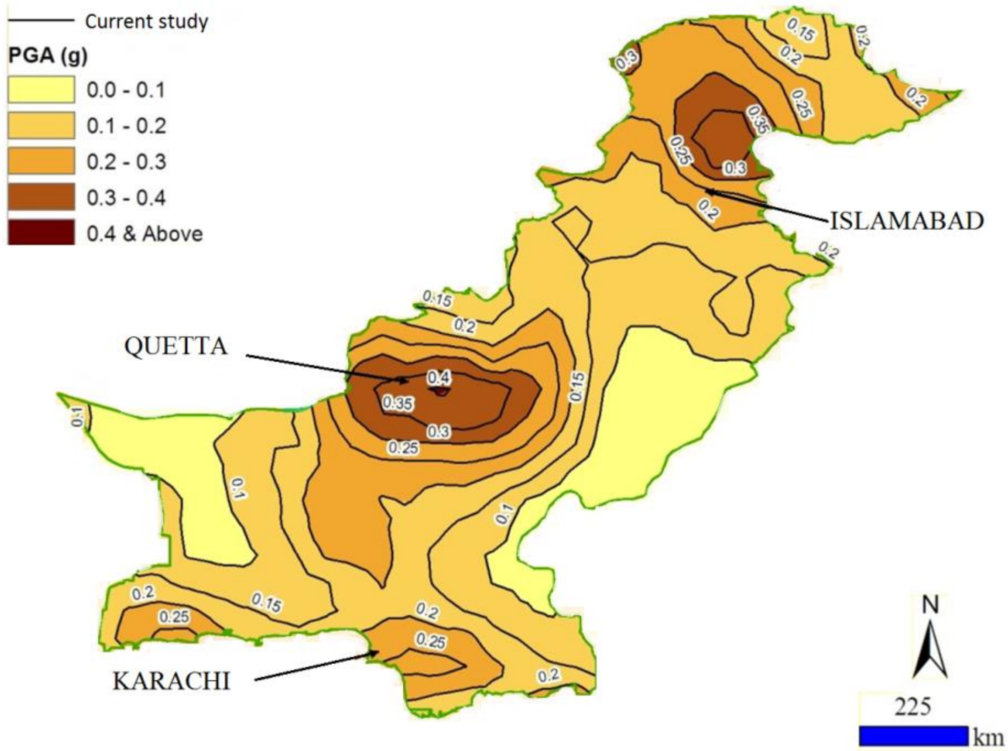


Figure 13. Seismic hazard map with 10% POE in 50 years using the proposed PSHA methodology

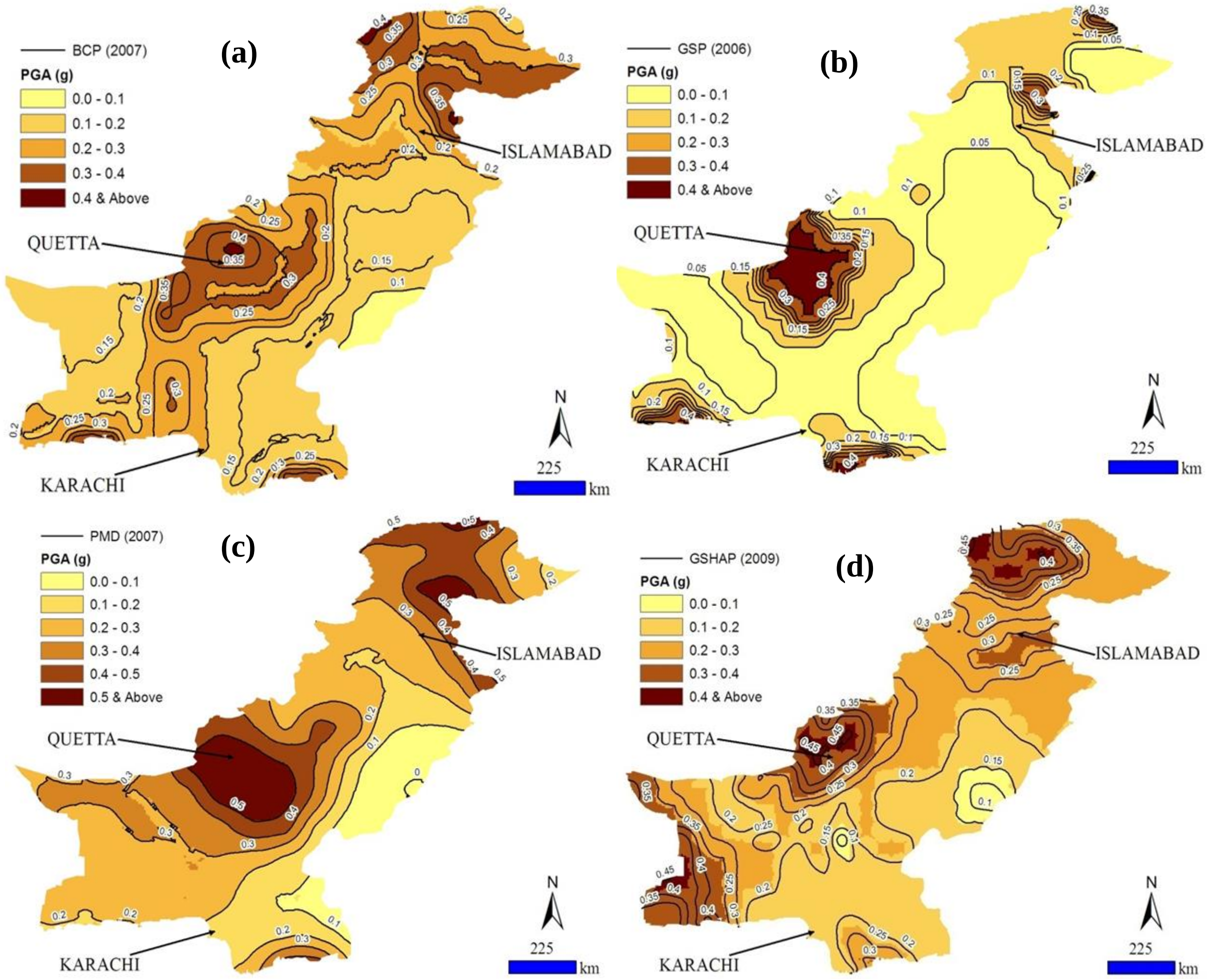


Figure 14. Seismic hazard maps for a 10% POE in 50 years according to (a) Building Code of Pakistan (BCP, 2007), (b) Geological Survey of Pakistan (GSP, 2006), (c) Pakistan Meteorological Department (PMD-NORSAR, 2007) and (d) Global Seismic Hazard Program (GSHAP) by USGS (2009)

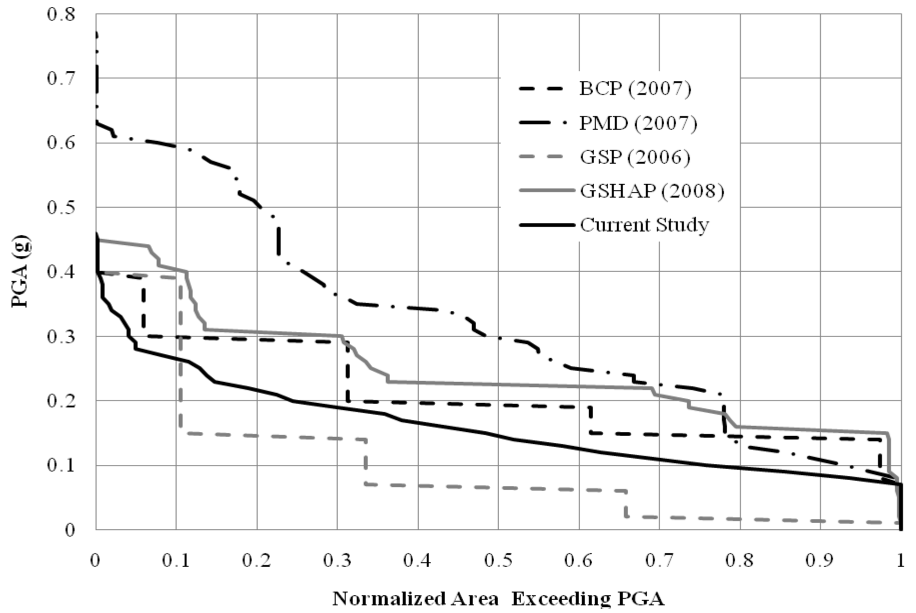


Figure 15. Normalized area exceeding a specific PGA level (50 year with 10% POE) based on different seismic hazard maps of Pakistan

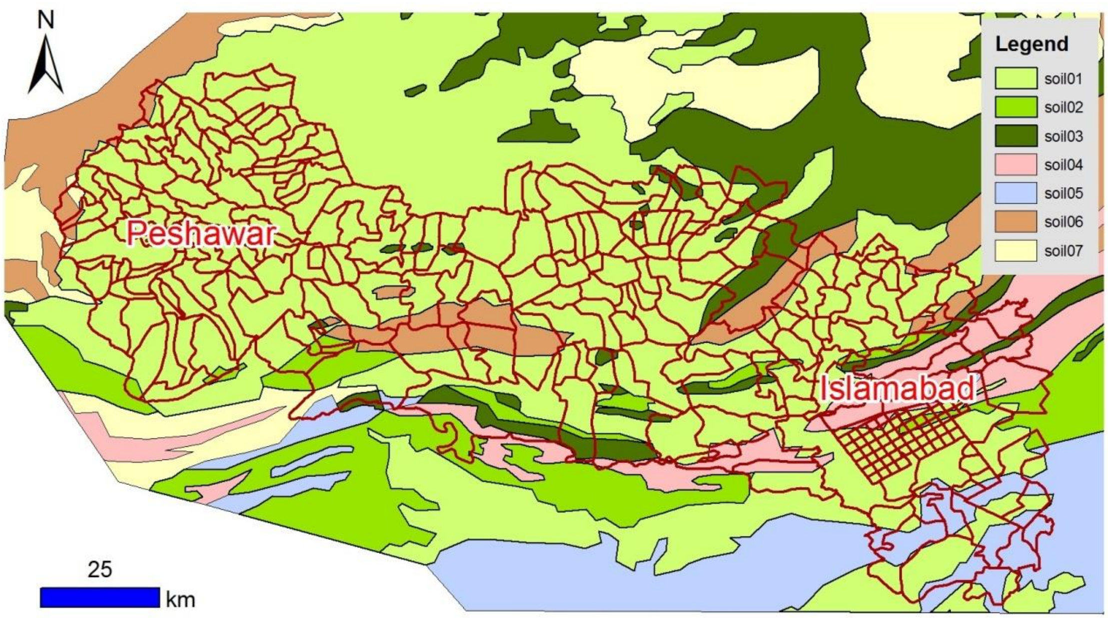


Figure 16. Soil typology map overlaid by the UCs within the study region

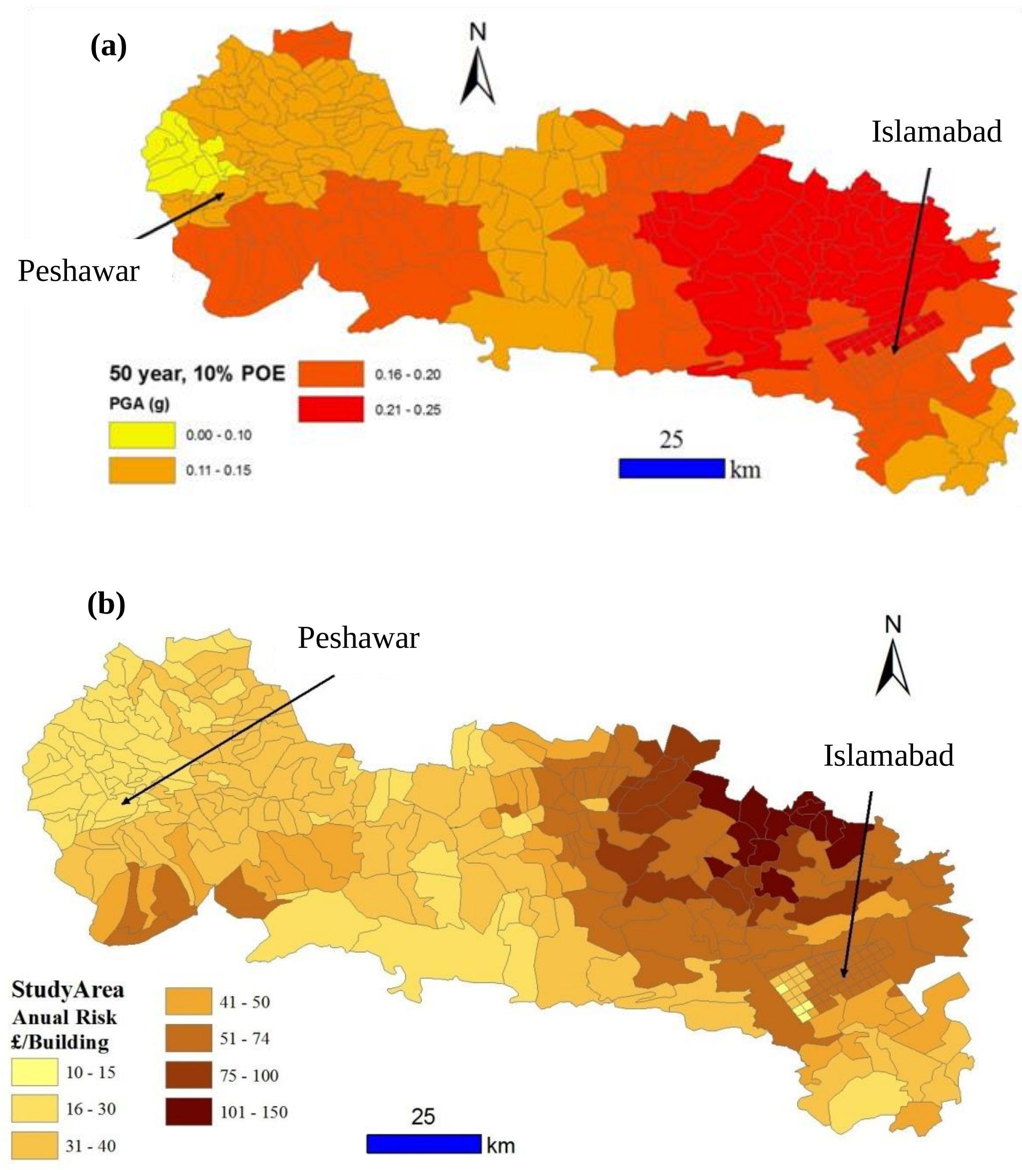


Figure 17. Results for hazard and monetary risk assessments by EQRAM applied to the study region (a) PSHA, (b) monetary risk assessment (NPV of 2008)

(a)

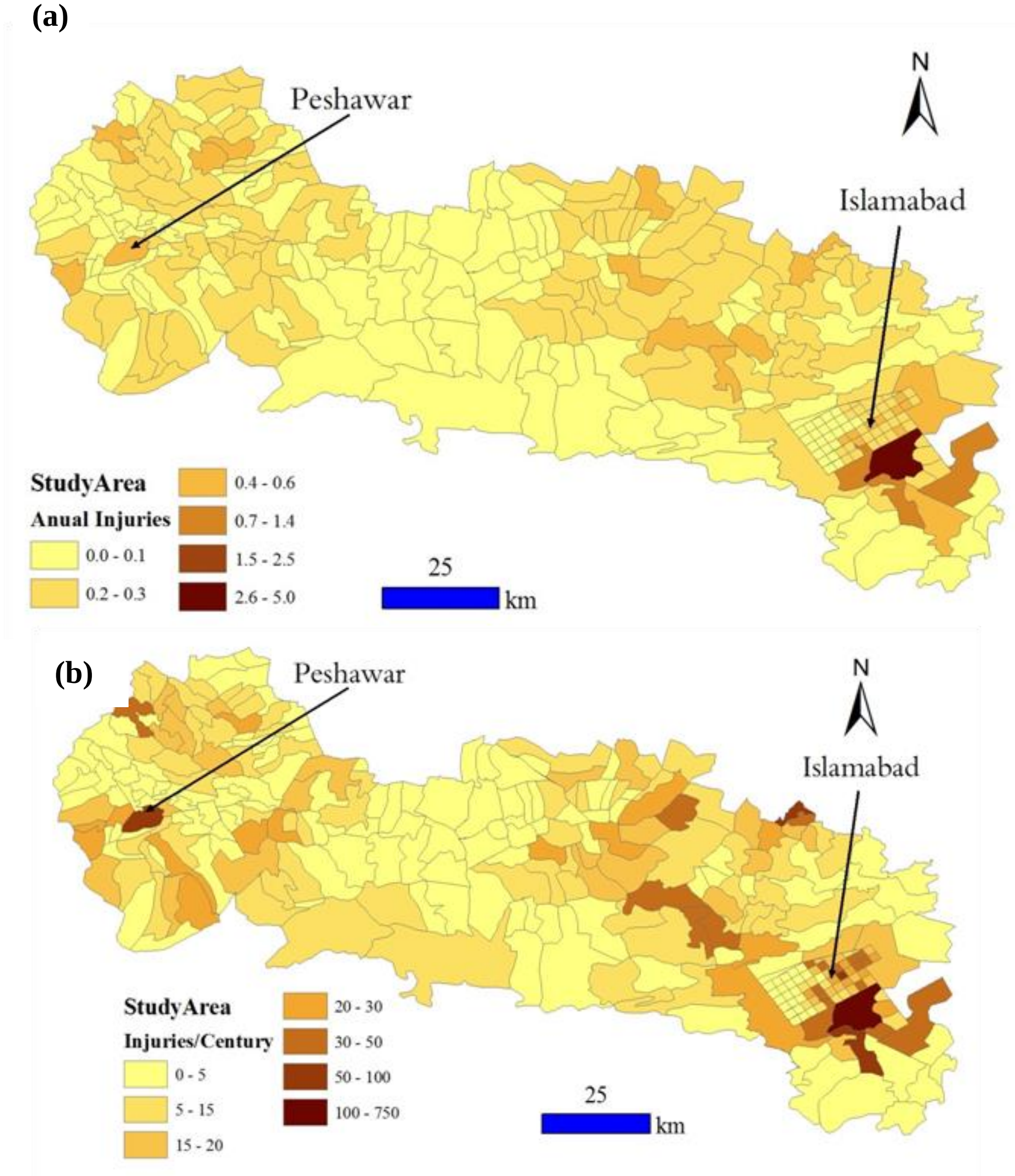


Figure 18. Results for casualty assessment by EQRAM applied to the study region (a) fatality risk and (b) injury risk (POE of 10% in 50 years, 2008 population data)

TABLES

Table 1. Inclusion of historical seismicity into the synthetic instrumental catalogues

		Magnitude Ranges				
		1	2	3	4	5
	Magnitude (M_w)	< 5	5 - 6	6 - 7	7 – 8	> 8
1	20th Century	$n^1{}_1$	$n^1{}_2$	$n^1{}_3$	$n^1{}_4$	$n^1{}_5$
2	19th Century	$n^2{}_1$	$n^2{}_2$	$n^2{}_3$	$n^2{}_4$	$n^2{}_5$
3	18th Century	$n^3{}_1$	$n^3{}_2$	$n^3{}_3$	$n^3{}_4$	$n^3{}_5$
4	17th Century	$n^4{}_1$	$n^4{}_2$	$n^4{}_3$	$n^4{}_4$	$n^4{}_5$
5	16th Century	$n^5{}_1$	$n^5{}_2$	$n^5{}_3$	$n^5{}_4$	$n^5{}_5$
6	15th Century	$n^6{}_1$	$n^6{}_2$	$n^6{}_3$	$n^6{}_4$	$n^6{}_5$
Total number of events		$\sum n^i{}_1$	$\sum n^i{}_2$	$\sum n^i{}_3$	$\sum n^i{}_4$	$\sum n^i{}_5$

Table 2. Tectonic characteristics of seismic zones

Zone	Name	Seismic Activity	Max. magnitude	General fault Direction (Bearing from North)	Fault mechanism
1	Kohistan-Kashmir	Very high	7.6	NW-SE (110°)	Thrust
2	Northern Balochistan	Very high	7.0	NE-SW (315°)	Thrust
3	Quetta-Sibi	Very high	7.5	E-W (285°)	Thrust
4	Southern Baluchistan	Low	5.0	NE-SW (320°)	Strike-slip
5	Northern Afghanistan-Tajakistan	High	6.0	E-W (265°)	Thrust
6	Hindu Kush	Very high	7.0	N-S (235°)	Strike-slip
7	North Western Afghanistan-Tajikistan Border Region	Very high	7.0	NE-SW (325°)	Thrust
8	Eastern Afghanistan	Low	4.0	NE-SW (320°)	Strike-slip
9	Makran Coast	Low	5.0	E-W (250°)	Thrust
10	Runn of Kuchch	High	8.1	NW-SE (115°)	Strike-slip
11	Sindh-Punjab	Very low	4.0	NE-SW (170°)	Strike-slip
12	Pamir Kunlun	Low	6.0	NW-SE (125°)	Thrust
13	Indian Kashmir	Low	6.0	NW-SE (95°)	Thrust
14	Upper Punjab-NWFP	Low	5.0	NE-SW (170°)	Thrust
15	Chitral	High	6.5	NW-SE (95°)	Thrust
16	Koh e Sulaiman	Low	4.0	NE-SW (170°)	Strike-slip
17	South West Iran	High	6.0	E-W (240°)	Strike-slip
18	Western Baluchistan	High	6.0	N-S (190°)	Strike-slip
19	Central Southern Afghanistan	Very low	4.0	NE-SW (320°)	Strike-slip

Table 3. Some major seismic events in Pakistan from the PMD-NORSAR catalogue

Place	Year	Latitude	Longitude	Magnitude/Intensity
Taxila	25AD	33.7	72.9	X
Dabul	893AD	24.8	67.8	VIII – X
Runn of Cutch	1819	23.3	68.9	IX – X
Kashmir	1828	34.1	74.8	X
Kashmir	1885	34.1	74.8	IX – X
Kangra	1905	32.1	76.3	8.0
Quetta	1935	29.5	66.8	7.7
Makran	1945	24.5	63.0	8.0
Kashmir	2005	34.5	73.6	7.6
Quetta	2008	30.5	67.4	6.4

Table 4. Instrumental and historical seismicity data of Pakistan categorized into different magnitude ranges

Centuries	Magnitude (M_w) Range					
	≤6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5-8.0	≥8.0
20th	9000	114	45	22	8	3
19th	101	5	4	5	2	0
18th	16	-	0	0	1	1
17th	-	-	3	0	0	0
16th	-	-	1	0	1	0
15th	-	-	1	2	0	1
14th	-	-	-	0	3	0
13th	-	-	-	1	1	0
Total Events	9117	119	54	30	16	5

Table 5. Formation of different soil types and S_S and S_A values in the study area.

Soil Type	Formation	Soil Type	S_S	S_A
Soil 01	Holocene: Unconsolidated, Silt, Clay, Sand and Gravel	Soft	1	0
Soil 02	Eocene and paleocene rocks: Shales, Limestone, Sandstone and Silts with Conglomerate.	Stiff	0	0.75
Soil 03	Pre-Cambrian and Jurassic rocks: Quartzite, Marble, Graphite Schist, Granite, Syenite and Diorite.	Rock	0	0
Soil 04	Miocene rocks: Siltstone, Sandstone, Conglomerate, Red-brown Mudstone and Hard Sandstone.	Stiff	0	0.25
Soil 05	Holocene: Silt, Sand and Gravel.	Soft	0.50	0
Soil 06	Pre-Cambrian metamorphic sedimentary and Carboniferous to pre-Cambrian rocks: Schist, Quartzite, Dolomite, Marble, Phylites, Limestone, and Slate.	Rock	0	0
Soil 07	Cambrian igneous rocks: mostly Granite and Leucocratetic Siliceous Gness.	Rock	0	0